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Amplitude Spectrum Modulation Technique for Analog Data Processing in Fiber Optic Sensing System With Temporal Separation of Channels

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Grigory Adamovsky
Lewis Research Center
Cleveland, Ohio

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Amplitude spectrum modulation technique for analog data processing in fiber optic sensing system with temporal separation of channels

Grigory Adamovsky

National Aeronautics and Space Administration, Lewis Research Center,
21000 Brookpark Road, Cleveland, Ohio 44135

ABSTRACT

A novel technique to analyze analog data in fiber optic sensing systems with temporal separation of channels is proposed. A theoretical explanation of the process is presented and an experimental setup that was used to obtain the data is described.

1. INTRODUCTION

Different referencing schemes for intensity modulation fiber optic sensing systems have been developed in recent years.[1] One of the schemes involves temporal referencing. To construct a system with the reference and signal channels separated in the time domain fiber optic loops are used.[2,3] An initial light pulse of a short duration sent into such a loop generates a series of pulses. The relative power of these pulses depends on the power losses in the loop. A sensor-transducer incorporated in the loop responds to the measured parameter and contributes to the losses. Thus, the information about the measured can be retrieved by measuring the relative power of the pulses. In the system employing the temporal referencing, the signal and reference channels share the same fiber optic link between the loop and signal processing electronics. This makes the system insensitive to changes in the transmission of the link and to light source intensity variations.

The major problem with this method lies in the fact that the entire fiber optic loop acts as a sensing element. To minimize the mentioned problem, the loop has to be short. However, in order to generate a pulse train, a shorter loop requires a shorter duration initial pulse. To process pulses of very short duration, high-speed oscilloscopes, boxcar averagers, or streak cameras have to be used. These measuring techniques require heavy and bulky equipment. However, in applications where size and weight play a considerable role, the use of stationary signal processing equipment is restricted. At the same time the conventional signal processing techniques employing small size high-speed analog components such as analog-to-digital converters and sample-and-hold circuits still require a significant fiber optic loop length and a relatively long duration initial pulse.

The technique proposed in this paper eliminates this problem. It is based on analyzing the amplitude spectrum of the signal and comparing different portions of the spectrum with each other.

2. THEORY

Assume we have a series of N rectangular pulses of the same duration t_1 and amplitudes $V_1, V_2, \ldots, V_N$, where N is a positive integer. Assume also that a delay between any two successive pulses is equal to Δ. Using Fourier analysis[4] the spectrum of this series of pulses can be written as follows:

$$F(jw) = F_1(w) \left\{ \sum_{n=1}^{N} \frac{V_n}{V_1} \exp\left[-j(n-1)w\Delta\right] \right\} \tag{1}$$

where

$$F_1(w) = V_1 t_1 \frac{\sin\left(\frac{wt_1}{2}\right)}{\frac{wt_1}{2}} \tag{2}$$

is a Fourier spectrum of the first pulse in the series and w is the angular frequency. Equation (1) can be rewritten in the form:

$$F(jw) = F_1(w)\left\{\sum_{n=1}^{N} \frac{V_n}{V_1}\cos[(n-1)w\Delta] - j\sum_{n=1}^{N} \frac{V_n}{V_1}\sin[(n-1)w\Delta]\right\} \tag{3}$$

The amplitude spectrum can be derived as:

$$F(w) = \left|F_1(w)\right| \left\{\left[\sum_{n=1}^{N} \alpha_n \cos(n-1)w\Delta)\right]^2 + \left[\sum_{n=1}^{N} \alpha_n \sin((n-1)w\Delta)\right]^2\right\}^{1/2} \tag{4}$$

where $\alpha_n = V_n/V_1$.

Analyzing the last expression for $N = 2$ (double pulse), Eq. (4) can be written as:

$$F(w) = \left|F_1(w)\right|[1 + \alpha^2 + 2\alpha\cos(w\Delta)]^{1/2} \tag{5}$$

where $\alpha = V_2/V_1$ is the pulse amplitude ratio.

Denoting the component in Eq. (5) that is dependent on the pulse amplitude ratio α, as $S(w,\alpha)$, then

$$S(w,\alpha) = [1 + \alpha^2 + 2\alpha\cos(w\Delta)]^{1/2} \tag{6}$$

This component will be referred to as the spectrum modulating function. The function S for different values of α is presented in Figure 1. This function of each value of α has maxima at $w = 2\pi(m-1)/\Delta$ and minima at $w = \pi(2m-1)/\Delta$, where m is a positive integer. Using the relationship $w = 2\pi f$ where f is the linear frequency one can find that the function described by Eq. (5) has maxima if $f = (m-1)/\Delta$ and minima if $f = (2m-1)/2\Delta$.

If the pulse amplitude ratio α varies, then for every given frequency w one can write the derivative with respect to α as:

$$\left.\frac{\partial F}{\partial \alpha}\right|_w = \left|F_1(w)\right| \frac{\alpha + \cos(w\Delta)}{[1 + \alpha^2 + 2\alpha\cos(w\Delta)]^{1/2}} \tag{7}$$

From the last equation it follows that if $\alpha > 1$, then $\partial F/d\alpha > 0$ for all frequencies. However, if $\alpha < 1$, some parts of the spectrum have $\partial F/\partial\alpha > 0$ and some have $\partial F/\partial\alpha < 0$.

The preceding equations show that different portions of the amplitude spectrum of a double pulse respond to a change in the pulse amplitude ratio α in different ways. At frequencies w corresponding to maxima of function $F(w)$, $\partial F/\partial\alpha > 0$ regardless of the value of α. However at frequencies corresponding to minima of the same function, $\partial F/\partial\alpha > 0$ only if $\alpha > 1$ and $\partial F/\partial\alpha < 0$ if $\alpha < 1$. For practical reasons the analysis can be restricted to the first extremes of the function $F(w)$. The ratio of the function $F(w)$ values obtained at the minimum to its value at the maximum as a function of α is:

$$R = \frac{\sin\left[\frac{(\pi t_1)}{(2\Delta)}\right](|1-\alpha|)}{\frac{(\pi t_1)}{(2\Delta)}(1+\alpha)} \tag{8}$$

The component $(|1-\alpha|)/(1+\alpha)$ as a function of α is plotted in Figure 2.

If a change in the ratio α is caused by some external factor (perturbation), the effect of the perturbation can be determined by analyzing the amplitude spectrum $F(w)$ of the double pulse and comparing different portions of the spectrum with each other. For the best sensitivity these spectral windows have to be located at the first maximum and the first minimum of the function $F(w)$, and the values of α have to be <1 because at these windows for $\alpha < 1$ the derivatives $\partial F/\partial\alpha$ have opposite sign.

In case the double pulse is repetitive with period T, the expression for the amplitude spectrum has to be written as:

$$F(w_p,\alpha) = \frac{1}{T} V_1 t_1 \left| \frac{\sin \frac{w_p t_1}{2}}{\frac{w_p t_1}{2}} \right| [1 + \alpha^2 + 2\alpha \cos(w_p\Delta)]^{1/2} \quad , \tag{9}$$

where $w_p = 2p\pi/T$ is the angular frequency ($p = 1,2,3, \ldots$) and the other equations have to be modified accordingly. However, if the double pulse period T is much greater than the delay Δ, the discrete frequencies w_p will be closely spaced and the above analysis will not be significantly changed.

2.1. Experimental setup

An experimental fiber optic sensing system consists of a pulse modulated light source, a fiber optic loop, a photodetector, and signal processing electronics. The fiber optic loop generates a light pulse train and together with a sensor incorporated in the loop forms a sensor head. The photodector detects the light pulse train, and the signal processing electronics processes the light pulses to obtain information about their relative amplitudes. Fiber optic cables link the light source, sensor head, and photodetector.

A schematic of the system is shown in Figure 3. A pulse modulated laser diode (PMLD) sends an initial pulse of short duration toward a sensor head via a fiber optic cable. The sensor head is formed by a semitransmitting-semireflecting mirror M1, a reflecting mirror M2, and a piece of fiber between the mirrors long enough to generate a train of pulses. For this method the first two pulses are employed, with the first pulse being the reference and the second one being the signal. These two pulses form a double pulse. A sensor incorporated in the loop reacts to the measurand by changing the amplitude of the second signal pulse. At the same time the first pulse does not pass through the loop, thus its amplitude remaines unchanged. The generated double pulse propagates back toward an avalanche photodetector (APD) along the same fiber optic cable. A 2x1 fiber optic coupler-splitter (C/S) provides isolation between the source and the photodetector. The signal processing electronics (SPE) retrieves information about the measurand by determining the pulse amplitude ratio α.

The pulse delay Δ in this configuration is equal to $2Ln/c$ where L is the length of the fiber in the loop, n is the group index of refraction, and c is the speed of light in vacuum. In the system used the fiber optic loop is 1.0 m long. Thus initial light pulse of 5 nsec duration and 10 kHz repetition rate results in a double pulse with 10 nsec delay between the pulses. The first minimum in the function $F(w_p,\alpha)$, which describes the amplitude spectrum of the double pulse, occurs at the frequency $f = 1/(2\Delta) = 50$ MHz. Observed signals with different pulse amplitude ratios α generated in the system and corresponding amplitude spectra are presented in Figure 4. The upper two pictures (Figure 4(a)) show the double pulse and the resulting spectrum for the case $\alpha > 1$, the two pictures in the middle (Figure 4(b)) for the case $\alpha = 1$, and the lower ones (Figure 4(c)) display the case $\alpha < 1$.

2.2. Signal processing

To process the pulses the following scheme shown in Figure 5 is used. A train of light pulses is detected by the APD, and the generated electric signal is split into two branches. One of the branches analyzes signals in a low-frequency band, another one processes high-frequency signals. Each of the branches consists of a bandpass filter, an amplifier, and a voltmeter. The bandpass filters are constructed by placing a lowpass and a highpass filters in series. The filters used in the low-frequency branch are four-pole Butterworth filters. The high frequency branch contains RF filters. An analog RF and a digital voltmeter are used in the high- and low-frequency branches respectively.

The following series of figures provides a complete picture of the transformation of the double pulse and its spectrum as the electronic signal propagates along each of the branches. Figures 6, 7, and 8 show the double pulse (left set of photographs) and its spectrum (right set of photographs) from APD (Figures 6(a), 7(a), and 8(a)) bandpass filter in the low-frequency branch (Figures 6(b), 7(b), and 8(b)), and bandpass filter in the high-frequency branch (Figures 6(c), 7(c), and 8(c)) for $\alpha > 1$, and $\alpha < 1$, respectively.

3. RESULTS AND DISCUSSION

Readings from voltmeters in the low- and high-frequency branches, V_{HF} and V_{LF} respectively, are compared, and the ratio of these readings is the measure of the pulse amplitude ratio α. Experimentally obtained dependence of the ratio V_{HF}/V_{LF} on the pulse amplitude ratio α is ploted in Figure 9.

In order to check the system stability of performance the amplitude of the initial light pulse has been changed and the ratio V_{HF}/V_{LF} has been measured. The experiment shows that a 20 percent change in the initial pulse amplitude results in the maximum change of about 2 percent in the ratio V_{HF}/V_{LF} for the values of $\alpha < 0.55$. This confirms that the proposed measuring technique makes the system insensitive to the light source intensity variations and variable connector losses.

The pulse amplitude ratio α is controlled by the coupling losses on the fiber-mirror interfaces, parameters of the mirrors, and losses in the fiber in the loop. Thus any of these factors can be used as a sensing mechanism to measure disturbances. This opens a potential of using the technique described with any kind of amplitude modulation sensors. Commerical availability of sources and detectors with bandwidth up to 10 GHz and possible utilization of small components for signal processing make the temporal separation of channels together with the amplitude spectrum modulation method a valuable remote sensing technique for aircraft applications.

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4. Schwartz, M., Information Transmission, Modulation, and Noise, 3rd Edition, McGraw-Hill, 1980.

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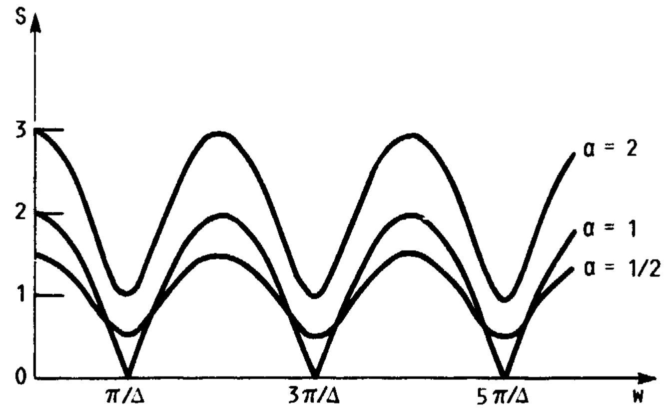


FIGURE 1. - THE SPECTRUM MODULATION FUNCTION S FOR DIFFERENT VALUES OF α.

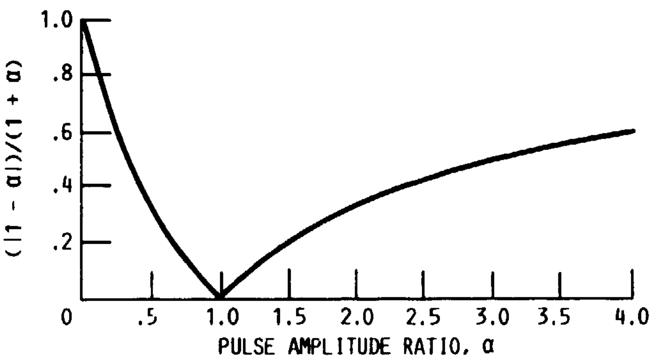


FIGURE 2. - A COEFFICIENT $(|1 - \alpha|)/(1 + \alpha)$ AS A FUNCTION OF THE PULSE AMPLITUDE RATIO α.

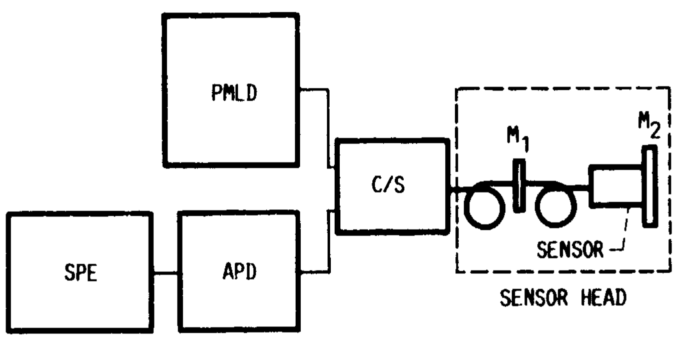
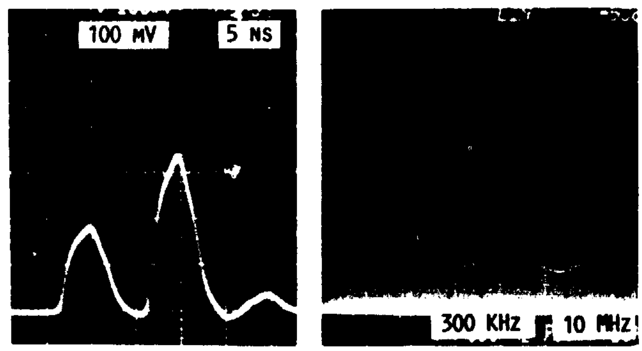
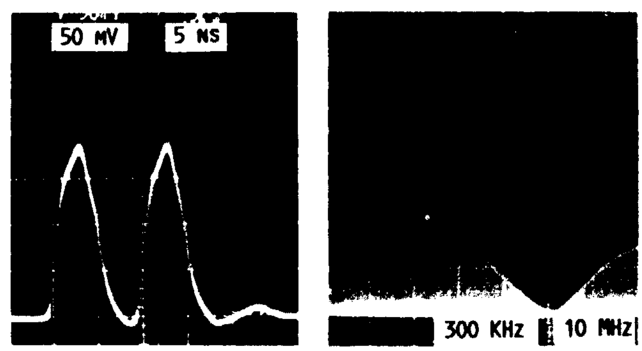


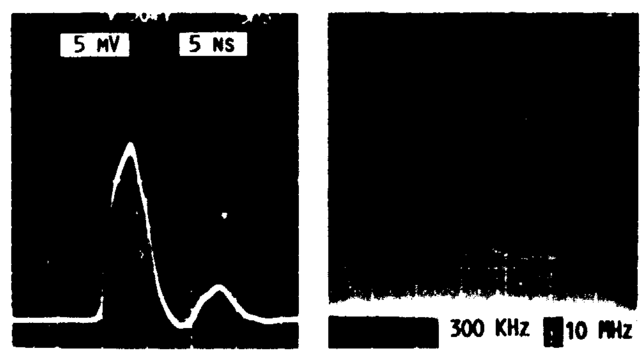
FIGURE 3. - SCHEMATIC CONFIGURATION OF THE SENSING SYSTEM. PMLD: PULSE MODULATED LASER DIODE; C/S: COUPLER-SPLITTER; APD: AVALANCE PHOTODETECTOR; SPE: SIGNAL PROCESSING ELECTRONICS; M_1: SEMIREFLECTING-SEMITRANSMITTING MIRROR; M_2: REFLECTING MIRROR.



(A) PULSE AMPLITUDE RATIO $\alpha > 1$.



(B) PULSE AMPLITUDE RATIO $\alpha = 1$.



(C) PULSE AMPLITUDE RATIO $\alpha < 1$.

FIGURE 4. - OBSERVED SIGNALS WITH DIFFERENT PULSE AMPLITUDE RATIO (LEFT SET OF PHOTOGRAPHS) AND CORRESPONDING AMPLITUDE SPECTRA (RIGHT SET OF PHOTOGRAPHS).

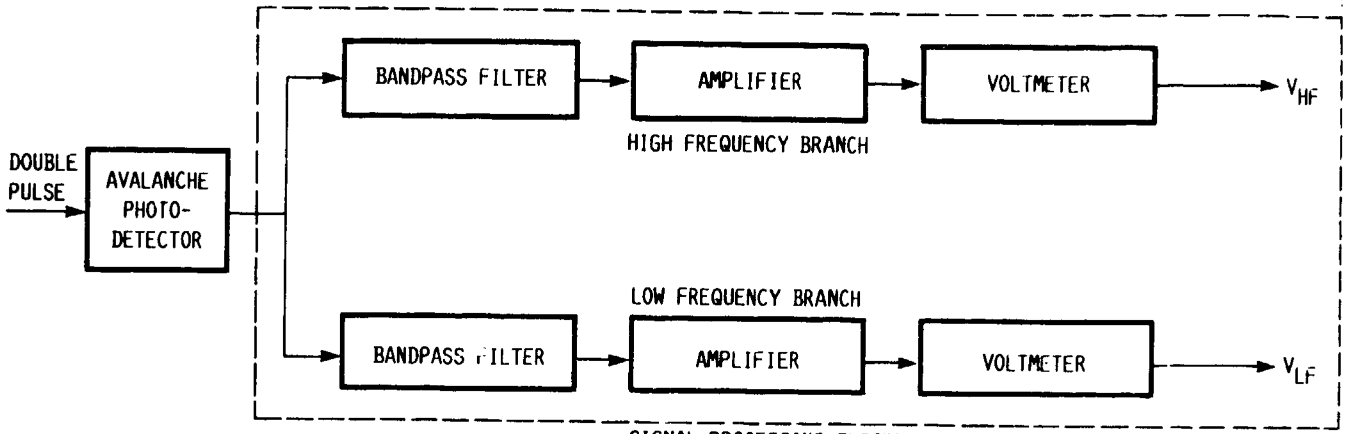
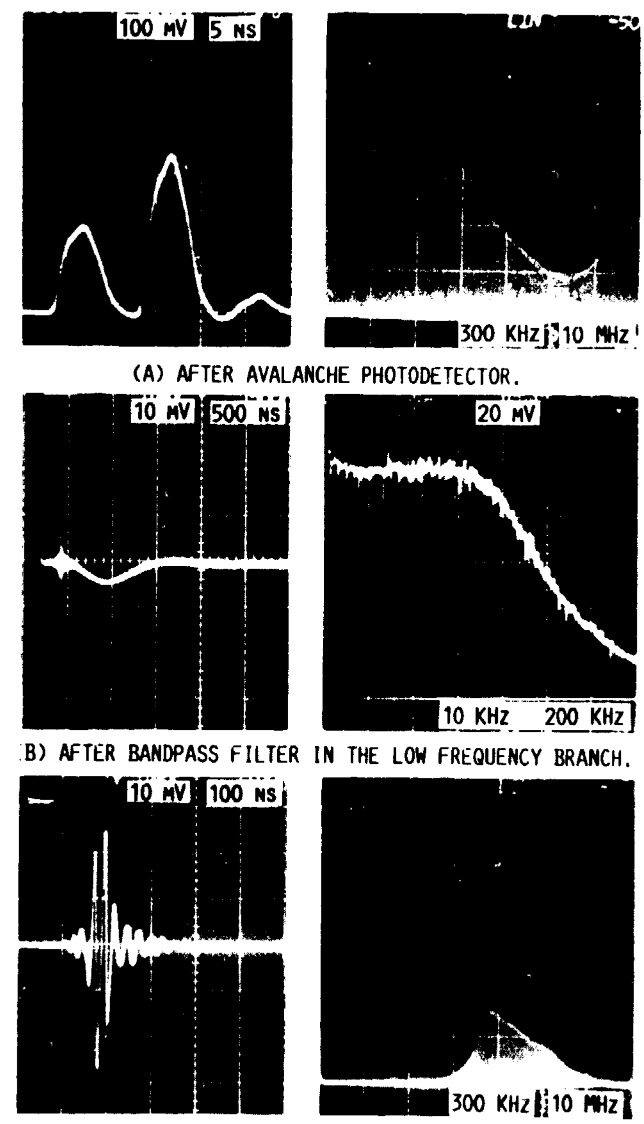


FIGURE 5. - SIGNAL PROCESSING SCHEME.

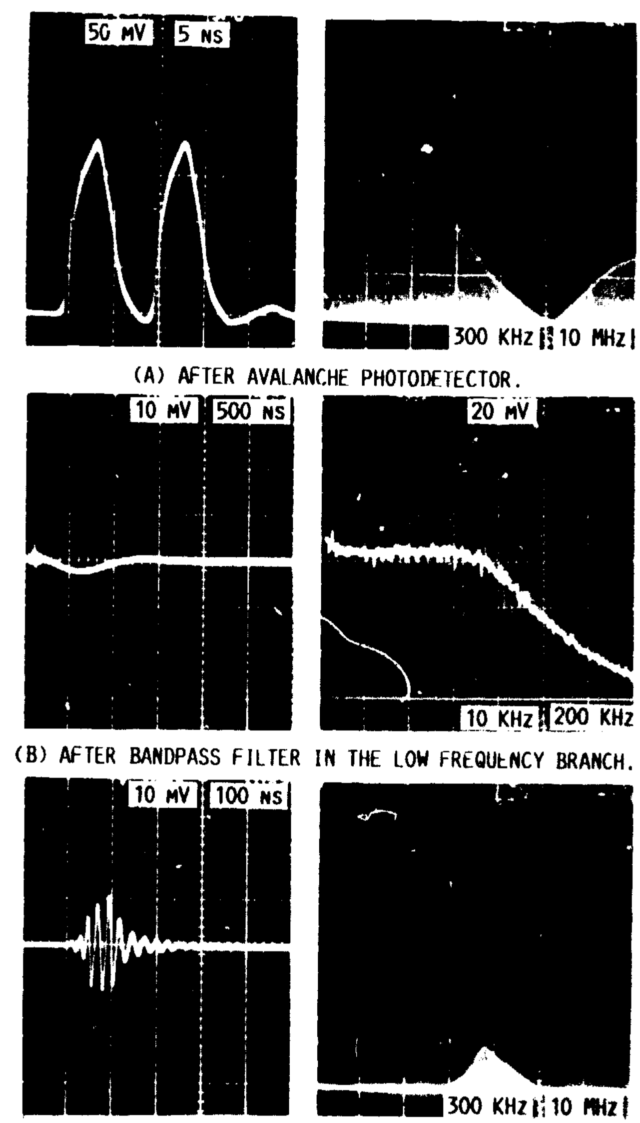


(A) AFTER AVALANCHE PHOTODETECTOR.

(B) AFTER BANDPASS FILTER IN THE LOW FREQUENCY BRANCH.

(C) AFTER BANDPASS FILTER IN THE HIGH FREQUENCY BRANCH.

FIGURE 6. - SIGNAL (LEFT SET OF PHOTOGRAPHS) AND ITS SPECTRUM (RIGHT SET OF PHOTOGRAPHS) FOR THE CASE $\alpha > 1$.



(A) AFTER AVALANCHE PHOTODETECTOR.

(B) AFTER BANDPASS FILTER IN THE LOW FREQUENCY BRANCH.

(C) AFTER BANDPASS FILTER IN THE HIGH FREQUENCY BRANCH.

FIGURE 7. - SIGNAL (LEFT SET OF PHOTOGRAPHS) AND ITS SPECTRUM (RIGHT SET OF PHOTOGRAPHS) FOR THE CASE $\alpha = 1$.

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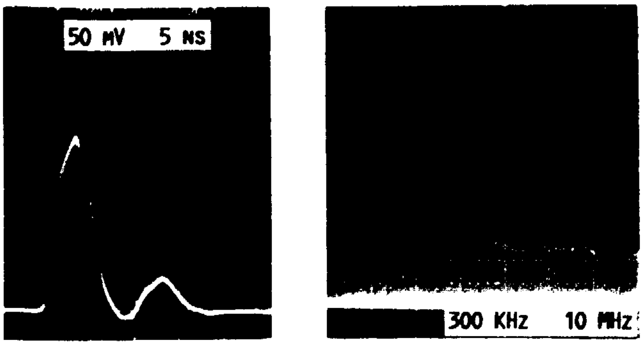
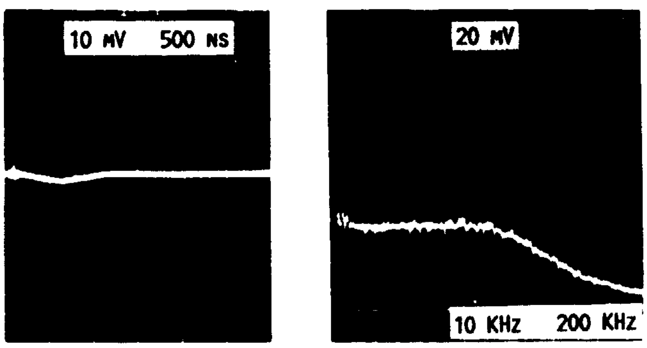
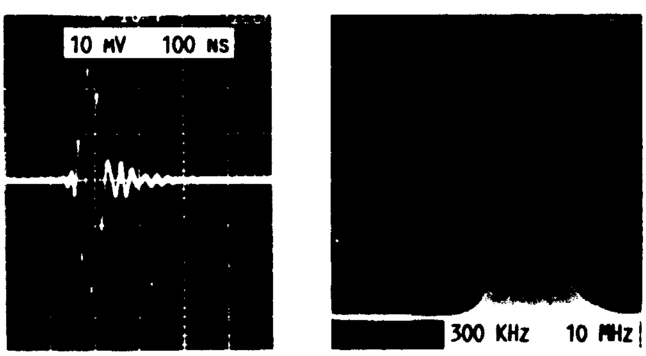


(A) AFTER AVALANCHE PHOTODETECTOR.



(B) AFTER BANDPASS FILTER IN THE LOW FREQUENCY BAND.



(C) AFTER BANDPASS FILTER IN THE HIGH FREQUENCY BAND.

FIGURE 8. - SIGNAL (LEFT SET OF PHOTOGRAPHS) AND ITS SPECTRUM (RIGHT SET OF PHOTOGRAPHS) FOR THE CASE $\alpha < 1$.

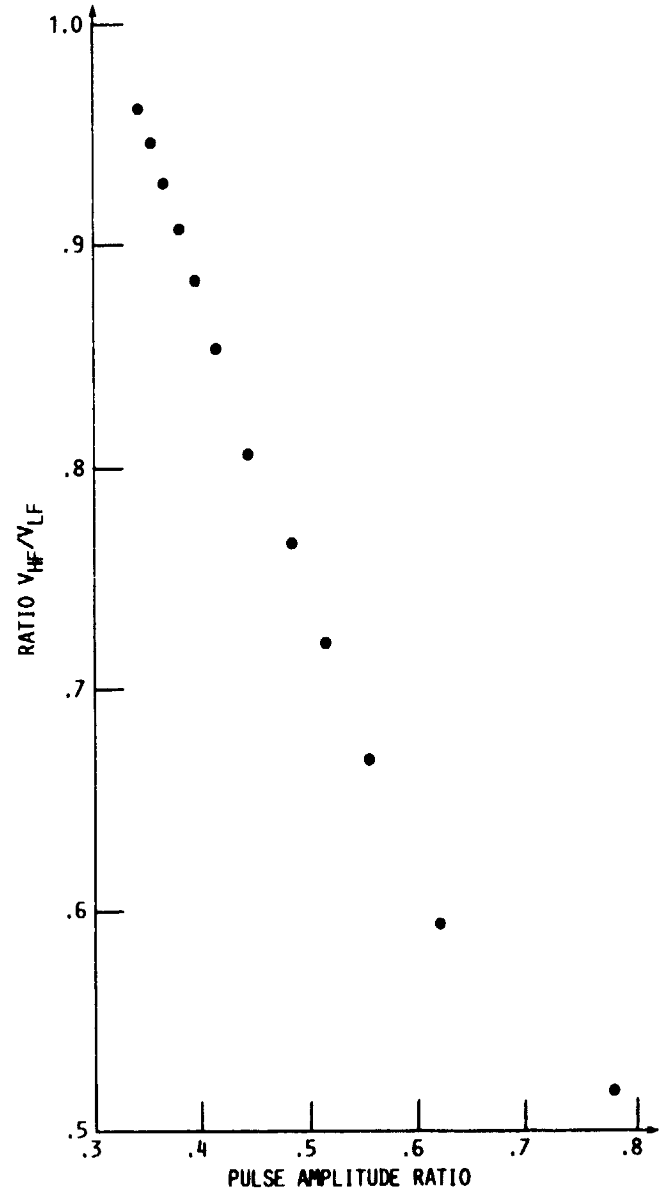


FIGURE 9. - EXPERIMENTALLY OBTAINED DEPENDENCE OF THE RATIO V_{HF}/V_{LF} ON THE PULSE AMPLITUDE RATIO α.

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